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Measuring the Brightness Temperature Distribution of Extragalactic Radio Sources with Space VLBI

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ABSTRACT

We have used VSOP space very long baseline interferometry observations to measure the brightness temperature distribution of a well-defined sub-set of the Pearson-Readhead sample of extragalactic radio sources. VLBI which is restricted to Earth-diameter baselines is not generally sensitive to emitting regions with brightness temperatures greater than approximately 10^{12} K, coincidentally close to theoretical estimates of brightness temperature limits, $10^{11} - 10^{12}$ K. We find that a significant proportion of our sample have brightness temperatures greater than 10^{12} K; many have unresolved components on the longest baselines, and some remain completely unresolved. These observations begin to bridge the gap between the extended jets seen with ground-based VLBI and the microarcsecond structures inferred from intraday variability, evidenced here by the discovery of a relationship between intraday variability and VSOP-measured brightness temperature, likely due to the effects of relativistic beaming. Also, lower limits on jet Lorentz factors, estimated from space VLBI observations, are starting to challenge numerical simulations that predict low Lorentz factor jets.

Subject headings: galaxies : jets — galaxies : active — quasars : general — radio galaxies : continuum — radiation mechanisms : non-thermal — techniques : interferometric

1. INTRODUCTION

Ground-based very long baseline interferometry (VLBI) surveys based on well-defined samples of extragalactic radio sources have been of critical importance in determining the general morphological and dynamical properties of the radio-bright jets originating in the nuclear regions of active galaxies (Pearson & Readhead 1988; Taylor et al. 1994; Moellenbrock et al. 1996; Kellermann et al. 1998) and have been essential in providing constraints and insights for theoretical models of nuclear jets and their environments. Studies of individual sources alone may provide a biased view of nuclear activity.

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The logical extension to this work is space-based VLBI surveys, which allow higher resolution images to be achieved at a given observing frequency. Also, the ability to measure brightness temperatures higher than possible from the ground, for a statistically useful number of sources, is one of the major justifications for extending the VLBI technique to space. Brightness temperatures measured with space VLBI can provide interesting constraints on jet formation models and the theory of relativistic beaming, based on comparisons of observed brightness temperatures with theoretical estimates of the intrinsic brightness temperature upper limit. If the jets in these sources are relativistic and somewhat aligned with our line of sight, the radiation from the jet can be apparently amplified, or Dopper boosted, causing the measured brightness temperature to be apparently in excess of the theoretical upper limit, yielding a lower limit on the jet Doppler factor.

We identify three theoretical estimates of the intrinsic brightness temperature upper limit, with which we will compare our observational data in subsequent sections: the inverse Compton limit of Kellermann & Pauliny-Toth (1969), 10^{12} K; the equipartition brightness temperature of Readhead (1994), 10^{11} K; and the induced Compton scattering limit of Sincell & Krolik (1994), 2×10^{11} K.

The first attempt to observe radio-loud AGN using space VLBI techniques was made by Levy et al. (1986) using the TDRSS satellite in conjunction with ground-based antennas. Linfield et al. (1989, 1990) describe measurements of brightness temperatures from these observations. The TDRSS observations demonstrated that space VLBI techniques were feasible, but the limited number of ground-based antennas meant that imaging was not possible.

We have conducted a space VLBI imaging survey using the facilities of the VLBI Space Observatory Programme (VSOP; Hirabayashi et al. 1998, 2000a), drawing our sample from the well-studied Pearson-Readhead survey of extragalactic radio sources (Pearson & Readhead 1981, 1988). Our survey has taken advantage of long space VLBI baselines and large arrays of ground antennas, such as the Very Long Baseline Array (VLBA) and European VLBI Network (EVN), to achieve high resolution images of 27 Active Galactic Nuclei (AGNs), and to measure the core brightness temperatures of these sources more accurately than is possible from the ground. This work complements the VSOP full-sky survey, which will observe most AGNs brighter than 1 Jy using a very limited set of ground-based antennas (Hirabayashi et al. 2000b).

The Pearson-Readhead sample contains 65 northern radio sources with 5 GHz flux densities greater than 1.3 Jy. Pearson & Readhead (1988) undertook global 5 GHz VLBI observations of this complete sample, detecting 46 sources in total. We have selected 31 of these on the basis of long Earth baseline 5 GHz flux density, > 0.4 Jy, as likely space VLBI detections above the 7σ level between a VLBA antenna and the orbiting antenna.

2. OBSERVATIONS AND DATA ANALYSIS

Observations using the HALCA orbiting antenna were conducted over the period 1997 August to 1999 April at a frequency of 5 GHz, in conjunction with either the VLBA, EVN, or in some cases, telescopes from both arrays. Typically HALCA was tracked between four and five hours per observation, producing (u,v) coverages with a maximum baseline of nearly 500 Mλ, or $30,000$ km. Full details of these data, the fringe-fitting, calibration, and imaging will be given in Lister et al. (2001).

The final clean images and the corresponding self-calibrated datasets were the basis for model-fitting analyses. The set of point source clean components describing each core were removed from the clean component model and replaced with a single elliptical Gaussian, described by 6 free parameters, which were fit to the *(u,v)* plane data using the MODELFIT task in DIFMAP (Shepherd, Pearson, & Taylor 1994). The visibility weights, derived from the scatter in the visibilities, used in this least squares fit were adjusted for the space baselines so that the sum of the weights on the space baselines equalled the sum of the weights on the ground baselines. In this manner, the ground antennas and the space antenna contributed equally to the reduced chi-squared statistic. The adjustment of weights on the space baselines is essential. Without adjustment the high SNR ground visibilities would dominate the model-fit. By increasing the weights on the space baselines we ensure that we include long baseline information in our Gaussian core models. Runs of MODELFIT were interspersed with phase self-calibration, to ensure that the reduced chi-squared was minimized to find the best fit models.

Errors on the parameters of the best-fit models were determined using the DIFWRAP package (Lovell 2000). We searched a four-dimensional parameter space in component major axis, axial ratio, position angle, and flux density for each source to determine which parameter ranges fit the *(u,v)* data. The sizes and flux densities of the model-fitted core components, and the errors on these quantities, were used to calculate limits on the observed brightness temperatures, assuming a Gaussian surface brightness profile for the core. We convert the Gaussian brightness temperatures to optically thick sphere brightness temperatures, by multiplying the Gaussian brightness temperatures by a factor of 0.56[9]. The observed frame, optically thick sphere brightness temperatures derived from our data are tabulated elsewhere (Lister et al. 2001).

To estimate lower limits on the Doppler factor we calculate $\delta_{\rm min} \sim (T_{\rm obs}(1+z)/T_{\rm int})$, where $\delta_{\rm min}$ is the minimum Doppler factor, $T_{\rm obs}$ is the observed brightness temperature, $T_{\rm int}$ is the intrinsic brightness temperature, and z is the source redshift. We discuss these lower limits in §3.1. To estimate limits on the brightness temperatures at a fixed frequency in the co-moving frame, so that we can meaningfully compare all the sources, we calculate $T_{\rm co} = T_{obs}(1+z)^{3-\alpha}$, where α is the observed spectral index ($S_{obs} \propto \nu_{obs}^{\alpha}$) and $T_{\rm co}$ is the co-moving frame brightness temperature (Readhead 1994). In the discussion of the co-moving frame brightness temperatures in §3.2 we adopt the optically thick case, $\alpha = 2.5$, to correspond to the physics embodied in the derivation of the theoretical brightness temperature limits. Support for considering the optically thick case as a reasonable approximation for the observed sources comes from those VSOP observations for which we have ground-based images at a similar epoch and resolution but higher frequency, from which we estimate core spectral indices. For this small number of sources the core spectral indices are substantially inverted.

Fig. 1 shows the resulting distribution of best fit brightness temperatures in the co-moving frame, for optically thick sphere profiles, and at a fixed frequency in the co-moving frame. For many sources the data provided only lower limits to the brightness temperature. The data for these sources are generally consistent with a zero axial ratio (i.e., one-dimensional) component with position angle equal to the position angle of the parsec-scale jet. This is possibly due to the presence of two or more closely spaced jet components in the core region that cannot be resolved individually. Data for 10% of the sources in our sample (0814+425, 1624+416, and 1637 + 574) are consistent with truly unresolved, point source cores. Although best-fit brightness temperatures were obtained with these zero-axial ratio and point source fits, the data are consistent within the errors with an infinite brightness temperature, giving only a lower limit to the brightness temperature. The set of flux vs *(u,v)* distance plots of our data given in Preston et al. (2000) illustrate this result in a different way, showing that the jets of many sources are resolved out on baselines just longer than an Earth

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[9]The Gaussian and optically thick sphere profiles are required to have the 50% points of their visibility functions occur at the same projected baseline, giving the ratio between Gaussian FWHM and optically thick sphere diameter to be 1.6 (Pearson 1995), resulting in the factor of 0.56 between the corresponding brightness temperatures

diameter, leaving only a marginally resolved or unresolved core component on the longest space baselines. For two sources, 4C 39.25 and 2021+614, the cores were too weak to constrain the model-fitting and both have unbounded upper and lower brightness temperature limits.

3. DISCUSSION

3.1. Upper limits to brightness temperature and lower limits to the Doppler factor

The highest brightness temperature lower limit we have found is 1.8×10^{12} K, for 0133+476 (in the observer's frame), prompting us to explore the physical mechanisms which can produce brightness temperatures in excess of theoretical intrinsic limits. The most popular current model is Doppler beaming, as discussed in the introduction. In this case our estimates of flux density are exaggerated, leading us to infer brightness temperatures higher than in reality. It is possible for a typical jet Lorentz factor $\Gamma = [1 - (v/c)^2]^{-1/2} = 5$ to boost the observed brightness temperatures up by a factor of $2\Gamma = 10$.

Kellermann & Pauliny-Toth (1969) derived an upper limit to the intrinsic brightness temperature of approximately 10^{12} K, based on the inverse Compton losses at high photon energies that occur when a synchroton plasma approaches 10^{12} K. The brightness temperature lower limits of three of our sources lie above 10^{12} K, implying the existence of Doppler boosting even in this extreme theoretical limit.

More recent theoretical work has shown that rather extreme conditions must be present in order for a synchrotron plasma to have an intrinsic brightness temperature near the inverse Compton limit. Readhead (1994) and Begelman, Rees & Sikora (1994) point out that the ratio of energy density in relativistic electrons to the energy density of the magnetic field must be extremely large (typically $\sim 10^7$) for the inverse Compton catastrophe to occur. For sources with milder energy density ratios (including those at equipartition, where $u_{rel} \simeq u_B$), Readhead (1994) has shown that their intrinsic brightness temperatures should lie close to 10^{11} K, which is an order of magnitude less than the inverse Compton limit. Sincell & Krolik (1994) have also considered the effects of induced Compton scattering by relativistic electrons in an AGN jet, and derive a hard limit to the brightness temperature of a self-absorbed synchrotron source to be approximately 2×10^{11} K. Although one cannot completely rule out the possibility that some AGNs may have extremely large u_{rel} to u_B ratios, it seems unlikely that this scenario is typical of the general AGN population, given the short lifetimes of sources radiating at the inverse Compton limit.

For 0133+476, the inverse Compton scenario gives a lower limit to the Doppler factor of approximately 3 and an upper limit of $\sim 19°$ on the jet viewing angle. If we adopt a more likely intrinsic brightness temperature of 10^{11} K, our estimate of the Doppler factor lower limit increases to ~ 30. The jet would have to be aligned to within only 2° of the line of sight in this case and the Lorentz factor lower limit would be $\Gamma > 15$. As numerical modeling of relativistic jets becomes more sophisticated, it appears to be difficult to produce jets from the vicinity of black holes with $\Gamma \gtrsim 3$ (Koide et al. 2000), which corresponds to the escape velocity from the inner edge of an accretion disk. These values are also much lower than the Γ's of up to ~ 40 needed to explain superluminal motions (e.g., Marscher et al. 2000). High Lorentz factor jets require the rapid acceleration of very light material outside the disk, such as a corona (Meier et al. 1997) or particles created near the horizon (Blandford & Znajek 1977). Even these processes are limited to $\Gamma \sim 10$ or so near the black hole by the drag force of photons emitted from the accretion disk (Levinson & Blandford 1995), although continued acceleration to higher speeds well beyond the central black hole is still possible (see, *e.g.*, Heinz & Begelman 2000). Therefore, direct measurements of brightness temperatures with space VLBI are beginning to challenge some theoretical models for relativistic jet formation in the inner regions of AGNs.

Alternatively, if non-equilibrium conditions exist then it is theoretically possible to exceed 10^{12} K for a synchrotron plasma (Slysh 1992). To exceed this value for long periods of time, energy would need to be continuously injected into the base of the jet. Other suggested mechanisms for producing high brightness temperatures in AGNs include coherent emission (Benford & Lesch 1998) and conical shocks (Spada, Salvati, & Pacini 1999).

3.2. Correlations with other source properties

We have gathered a vast amount of supporting data from the literature on our sample, in order to look for possible correlations between VSOP-measured quantities and other source properties. A full multi-dimensional correlation analysis of our sample will be presented in Lister, Tingay, & Preston (2001). Here we discuss our results concerning the VSOP core brightness temperatures.

As many of our brightness temperature measurements involve lower limits, we used a non-parametric Kendall's tau test from the ASURV Rev 1.2 survival analysis package (Lavalley, Isobe, & Feigelson 1992) to establish the statistical likelihood of possible correlations. Interestingly, we did not find any correlations between co-moving frame brightness temperature and potential beaming indicators such as core dominance, jet bending, spectral index, emission line equivalent width, and percentage optical polarization. This may be due to the large number of lower limits in our dataset, which hinders the detection of statistically robust correlations.

We have also performed a series of Gehan's generalized Wilcoxon two-sample tests (Gehan 1965) on our data, to investigate whether objects of various AGN classes have different co-moving frame brightness temperatures, at the 95% confidence level. We find no statistically significant differences in the distributions of a) quasars versus BL Lac objects, b) high-optically polarized quasars ($m_{opt} > 3\%$) versus low-optically polarized quasars, and c) EGRET-detected versus non-EGRET detected sources.

One source property which does appear related to co-moving frame brightness temperature is intraday variability (IDV). This phenomenon, in which a source displays variability on timescales of a day or less, occurs in roughly 30% of all compact radio sources (Quirrenbach et al. 1992). The rapid nature of these fluctuations implies very small source sizes, and in turn, high brightness temperatures (Dennett-Thorpe & de Bruyn 2000; Kedziora-Chudczer et al. 1997). Quirrenbach et al. (1992) have divided IDV activity into three classes: class II consists of rapid up-and-down flux density fluctuations, class I involves monotonic increases or decreases on short timescales, and class 0 indicates no IDV. In Lister et al. (2001) we list the IDV classification for the sources in our sample that have been monitored for IDV. Some sources display different classes of IDV activity at different times: for these objects we list the maximum class of IDV published in Quirrenbach et al. (1992, 2000) and Krichbaum, Quirrenbach, & Witzel (1992). We find that the class II sources have higher co-moving frame core brightness temperatures than the class 0 and class I sources, at the 98.0% and 97.8% confidence levels, respectively.

Although this finding appears to imply a close relationship between the compactness of the core and IDV activity, the co-moving frame brightness temperatures are significantly smaller than those implied from the IDV timescales (i.e., 10^{15-21} K), if they are intrinsic to the source. Part of this difference might be due to the differing effects of Doppler factor on the brightness temperature estimates. Brightness temperature estimates from IDV should be a factor of δ^2 higher than from VLBI, since they depend on timescale measurements (Teräsranta & Valtaoja 1994). Any remaining difference may be explained if a contribution to the observed IDV is due to interstellar scintillation (Kedziora-Chudczer et al. 1997).

Quirrenbach et al. (1992) find that virtually all sources with compact VLBI structures show IDV at a level greater than 2% of total flux, indicating a relationship between IDV and relativistic beaming. We have found further evidence for such a relationship by using space VLBI to probe these compact structures, measuring core brightness temperatures, which are directly related to the Doppler factors of their jets. It seems likely that the relationship we find between IDV type and VSOP-measured brightness temperature is partly due to Doppler boosting. High Doppler factors will boost brightness temperatures to high values and will also decrease the timescale of any intrinsic variations in flux, as seen in the observer's frame; a timescale intrinsic to the source of Δt corresponds to a timescale in the observer's frame of $(1+z)\Delta t/\delta$. This could tend to give highly beamed sources high apparent brightness temperatures and type II IDV, whereas less beamed sources will have lower apparent brightness temperatures and type 0 or I IDV.

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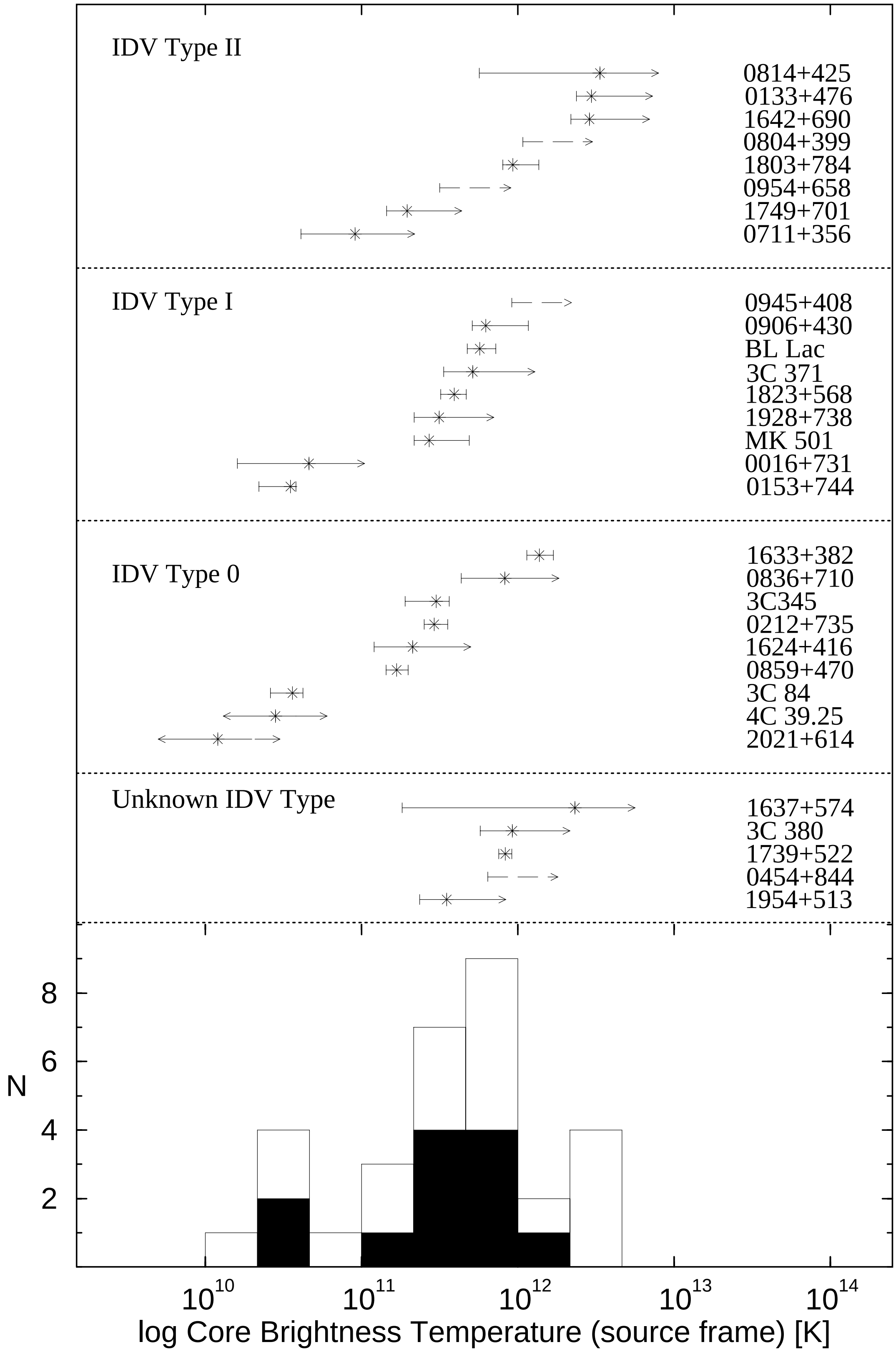

Fig. 1.— Top panels: plots of co-moving frame, optically thick brightness temperatures for the cores of Pearson-Readhead AGNs, grouped by IDV class. Sources indicated with dashed lines have not yet been observed with VSOP. Bottom panel: histograms of best-fit core brightness temperature for the entire sample (unshaded), and only those sources with measured lower and upper limits on brightness temperature (shaded).